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ORIGINL RESEARCH

Feasibility analysis of a novel non-invasive ultrasonographic method for the measurement of intra-abdominal pressure in the intensive care unit

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Abstract

Increased intra-abdominal pressure (IAP) is an important vital sign in critically ill patients and has a negative impact on morbidity and mortality. This study aimed to validate a novel non-invasive ultrasonographic approach to IAP measurement against the gold standard intra-bladder pressure (IBP) method. We conducted a prospective observational study in an adult medical ICU of a university hospital. IAP measurements using ultrasonography by two independent operators, with different experience levels (experienced, IAP_{US1}; inexperienced, IAP_{US2}), were compared with the gold standard IBP method performed by a third blinded operator. For the ultrasonographic method, decremental external pressure was applied on the anterior abdominal wall using a bottle filled with decreasing volumes of water. Ultrasonography looked at peritoneal rebound upon brisk withdrawal of the external pressure. The loss of peritoneal rebound was identified as the point where IAP was equal to or above the applied external pressure. Twenty-one patients underwent 74 IAP readings (range 2–15 mmHg). The number of readings per patient was 3.5 ± 2.5, and the abdominal wall thickness was 24.6 ± 13.1 mm. Bland and Altman's analysis showed a bias (0.39 and 0.61 mmHg) and precision (1.38 and 1.51 mmHg) for the comparison of IAP_{US1} and IAP_{US2} and vs. IBP, respectively with small limits of agreement that were in line with the research guidelines of the Abdominal Compartment Society (WSACS). Our novel ultrasound-based IAP method displayed good correlation and agreement between IAP and IBP at levels up to 15 mmHg and is an excellent solution for quick decision-making in critically ill patients.

Keywords Compartment syndrome · Critical illness · Intensive care unit · Intra-abdominal hypertension · Abdominal pressure · Measurement · Bladder pressure · Ultrasonography

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1 Introduction

Intra-abdominal pressure (IAP) is a vital sign in critically ill patients [1–4], with a high prevalence of intra-abdominal hypertension (IAP > 12 mmHg) seen in various patient groups including the surgical (trauma, burns, cardiac) as well as medical (sepsis, liver cirrhosis, acute kidney injury) patients [5]. Intra-abdominal hypertension (IAH) can lead to multi-organ dysfunction and failure, making early detection of IAH essential to prevent abdominal compartment syndrome. Late detection of IAH can also lead to a more severe condition, known as poly-compartment syndrome, due to organ cross-talk in the body [6]. The measurement of IAP is therefore crucial for early detection and subsequent treatment strategies in critically ill patients.

The actual gold standard for IAP measurement; advocated by the Abdominal Compartment Society (www.wsacs.org) is an indirect measurement methodology through the bladder [3]. However, the intra-vesical measurement method is a non-continuous method and can increase the risk of late IAH detection. Also, careful attention should be paid to the patient's position and the volume of saline instilled into the bladder [7]. Small changes to the transducer position can also affect the results significantly, showing IAP values up to 3.8 mmHg higher than the correct reference position [8]. Moreover, this measurement method is not applicable to patients with intra-pelvic masses since any tumor near the bladder can result in erroneous IAP readings via the bladder. Other IAP measurement alternatives have been explored, such as clinical examination [4], direct measurement through a peritoneal catheter [9], biomarker assessment [10], tensiometry [10], bio-impedance [11], and microwave-based techniques [11–14]. However, these methods have limitations such as lack of accuracy, risk of bleeding and trauma, and insufficient validation studies, preventing them from being the ultimate solution for IAP measurement.

[10, 11, 16, 12, 12–15]. In this study, a novel non-invasive IAP measurement method based on ultrasonography has been proposed. The concept behind this methodology is based on the balance between the IAP and external abdominal pressure, and peritoneal rebound in response to the brisk removal of the external pressure being applied to the anterior side of the abdominal wall. As a feasibility analysis, IAP evaluation based on this novel approach has been validated against the actual gold standard (intra-bladder measurement method).

The aim of this investigation is to introduce a novel, easy to use, non-invasive IAP assessment technique that can be used in ICU patients. This methodology can also be used at hospitals with poor infrastructure in low-income regions, which can improve patient care significantly. The outcome of this study will trigger further research on this methodology as well.

2 Materials and methods

2.1 Patient selection

The study included adult patients without underlying pathology of the anterior abdomen, with a clinical suspicion of IAH, and with an existing indwelling urinary catheter attached to a pressure transducer. Since the lack of respiratory-induced IAP oscillation is a sign of erroneous IAP reading through the bladder, patients were excluded if their intra-bladder pressure time readings did not show any respiratory variation due to pathologies affecting bladder compliance. Having this selection criteria into account, twenty-one adult patients were included within a period of six months in this study.

The study was conducted in accordance with the study protocol, the Declaration of Helsinki, and applicable regulatory requirements. The study protocol was approved by the institutional review board of the local ethics committee (study number B/09/032) and written informed consent was obtained from each patient prior to inclusion.

2.2 IAP measurement using the ultrasonographic method

The hypothesis of this novel IAP evaluation method is based on the fact that the peritoneal lining can be affected by exerting external pressure to the abdominal wall. In fact, the peritoneal lining position is influenced by the internal pressure of the abdominal compartment (IAP) and the external pressure on the abdominal wall. If the external pressure on the abdominal wall is smaller than the IAP, the peritoneal lining follows the shape of the abdominal compartment. However, when the external pressure on the abdominal wall is higher than a certain threshold, it distorts the peritoneal lining. In a similar way, when the external pressure is being removed abruptly, the peritoneal rebound happens to bring back the original shape of the abdominal compartment. Since the peritoneum is the deepest tissue of the abdominal wall and closest tissue to the abdominal compartment, its lining will be changed when the pressure from one side is higher than the other side. Therefore, this balance point between the internal (IAP) and external abdominal pressure, and subsequently, the peritoneal rebound due to the brisk removal of the external force can be used to evaluate the IAP in an indirect and non-invasive way.

According to the mentioned hypothesis, a standard cylindrical bottle with a weight of 100 g, a constant diameter

of 8 cm (up to 19 cm in height) and a cross-sectional area of 50 cm2 was used to apply a controlled external pressure to the abdominal wall. The soft abdominal adipose and connective tissue would be depressed and distorted by the bottle weight. However, this distortion will be transferred to the peritoneum if the external pressure is equal to or higher than IAP. Therefore, the loss of peritoneal rebound was interpreted as the case when IAP was equal to or above the applied external pressure to the abdominal wall. Since the density of water was 1 g/cm3, each 1 cm of water column in the container added 50 g of weight to the abdominal wall. The external pressure value on the abdominal wall can be calculated with the cross-sectional area of the bottle by using Eq. 1.

$$ExternalPressure = \frac{(50 \times h + 100)}{50} = h + 2[cmH2O] \quad (1)$$

Where h is the water column height in cm.

Subsequently, the external pressure can be converted to mmHg by using Eq. 2.

$$ExternalPressure = \frac{(h+2)}{1.36}[mmHg] \quad (2)$$

The maximum pressure that could be exerted using the bottle (marked at intervals of 1 cm) was thus 19 + 2 = 21 cmH2O, which was equivalent to 15.4 mmHg. Patients were placed in a supine position, with the anterior abdominal wall relaxed prior to each IAP assessment [15]. Subsequently, the bladder was drained via the indwelling Foley catheter, and an external pressure of 15.4 mmHg was exerted to the mid-abdomen area. The ultrasound transducer was positioned next to the area where the external pressure was exerted. The bottle was then abruptly lifted off the abdomen at end-expiration and the peritoneal lining was carefully screened for a rebound (Fig. 1). The height of the water column was reduced by 0.5 cm when rebound was detected and the experiment was repeated until peritoneal rebound no longer occurred. The value of the external pressure at that moment was assumed to be equal to the IAP inside the abdominal compartment. Two video clips are also provided in online resources 1 and 2 to present a better illustration of this novel methodology.

Two independent operators (blinded to each other's results and measurement procedure) performed two sets of IAP measurements using this ultrasonography method. The first set of measurements (IAP_{US1}) was completed by an operator experienced with general thoracic and critical care ultrasonography. No additional training was provided for the first operator as he already knew this measurement concept. The second set of measurements (IAP_{US2}), however, was performed by any other medical ICU team member without previous experience in ultrasonography and who was taught this ultrasonographic-based IAP method by the first operator. Since the second operator was from the medical ICU team and already experienced with the application of the ultrasound-based monitoring techniques, the training included the measurement procedure (brisk removal of the external pressure and peritoneal rebound screening at end-expiration) only, and no training on the ultrasonography was needed. Hence, a series of 21 different operators were used for the second set of measurements. Since each patient was evaluated by two different observers, the interobserver variability impact on the results can be assessed as well. The convex transducers used included the P17 5 – 1 MHz or C60e 5 – 2 MHz transducers attached to the MicroMaxx® (Sonosite Inc, Bothell, WA, USA) machine, or the C15 4 – 2 MHz transducer attached to the 180PLUS® (Sonosite Inc, Bothell, WA, USA) machine. Each patient was evaluated at least twice per day with a time interval of approximately 8 h between measurements, until removal of the urinary catheter or the pressure transducer by the attending clinical team.

2.3 IAP measurement using the intra-bladder technique

Immediately following the ultrasonographic evaluation, an independent third operator (blinded to the ultrasound results) measured IBP as previously described [16]. The bladder was emptied prior to each IBP measurement, and the aspiration side-port was connected to a set of three stopcocks (one each for zeroing, attaching a 20 ml syringe, and a 500 ml bag of normal saline) in line with a pressure transducer. Correct pressure signal transduction was ensured by observing respiratory variations of the pressure-time curve with an inspiratory increase and expiratory decrease, and the oscillations after gentle abdominal compression/decompression [17]. If the pressure signal was dampened, the clamp was opened, residual saline was drained to flush out any air bubbles and 20 ml of fresh saline was re-instilled [18]. The lowest end-expiratory pressure reading was derived from the pressure-time tracing measured with the aid of the freeze screen option of the bedside monitor and an on-screen cursor.

2.4 Statistical analyses

Results are presented as mean and standard deviations (± SD) in cases of normal distribution. Pearson's correlation and linear regression analyses were used initially. Two methods were considered equal if the line of identity crossed the origin of the X and Y-axes and if R^2 (R = Pearson's correlation coefficient) was greater than 0.6. The intra-class

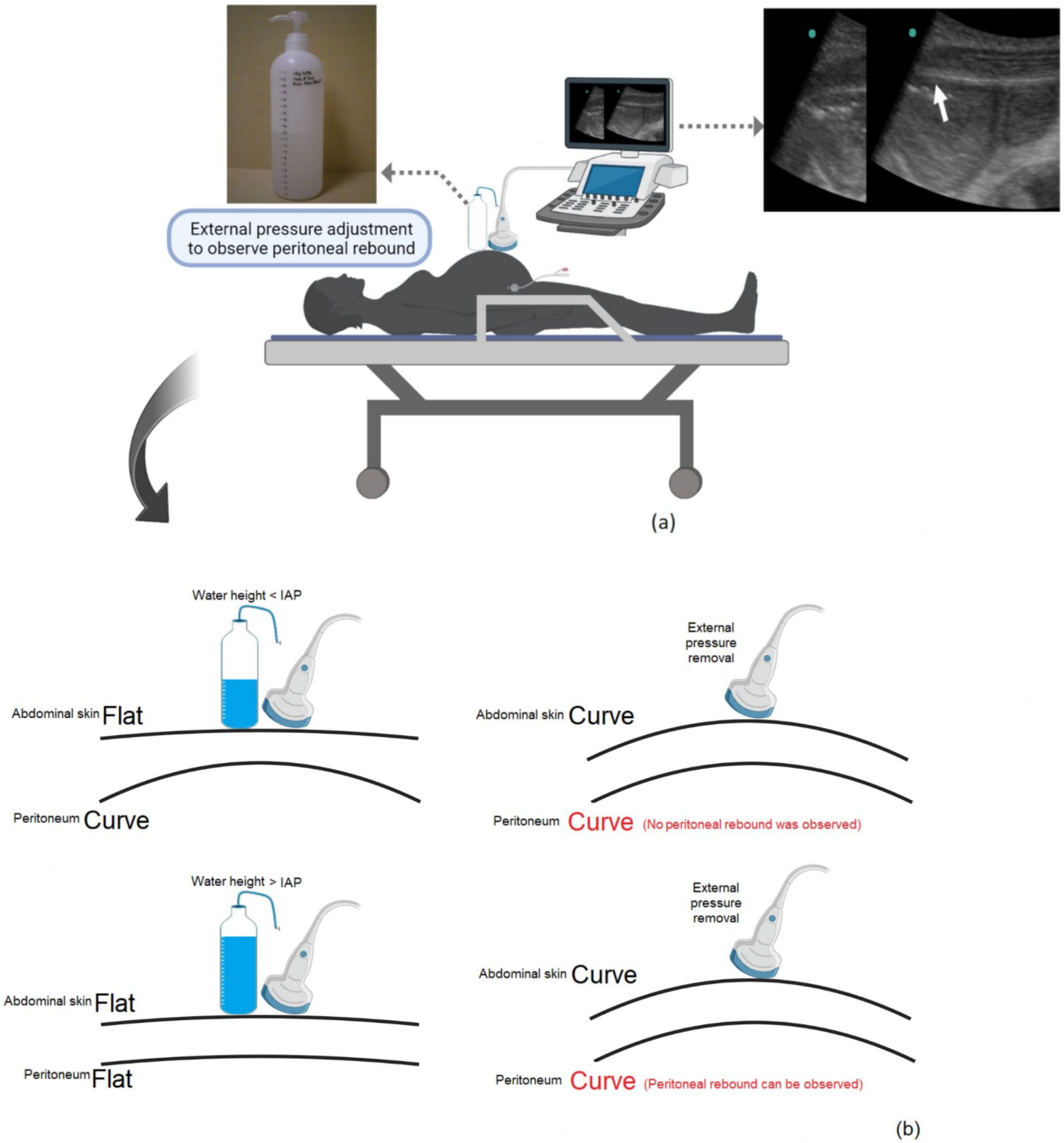

Fig. 1 An illustration of the IAP measurement procedure by means of ultrasonography in combination with external pressure. **a**. In addition to IAP_{US}, a third operator measured the intra-bladder pressure (IBP) using a Foley catheter. **b.** Pictorial representation of peritoneal rebound. The pictures on the left show peritoneal rebound occurring as the external pressure applied by the bottle exceeds the IAP. The pictures on the right show absence of peritoneal rebound as IAP exceeds the externally applied pressure

correlation (ICC) coefficient between the ultrasonography (both IAP_{US1} and IAP_{US2}) and IBP results was also evaluated to check the measurement reliability. The bias, defined as the mean difference between IAP_{US} and IBP, was calculated. Subsequently, precision (defined as the SD of the bias) and limits of agreement (LA, defined as the bias ± 1.96 precision) were calculated according to Bland and Altman [19]. The percentage error was calculated by multiplying the precision by two and dividing the result by the mean IAP values of that technique. Finally, the ability of IAP_{US} to

track changes or trends in IBP was assessed by plotting the ΔIAP_{US} against ΔIBP during the same time interval (four quadrants trend plot). The concordance coefficient was then calculated as the percentage of pairs with the same direction of change after exclusion of pairs, with both a ΔIAP_{US} and $\Delta IBP \leq 2.5$ mmHg (or less than 15% of change) and exclusion of pairs with either ΔIAP_{US} or ΔIBP equal to zero [20]. Statistical analysis was performed using Excel (Microsoft Excel 2007, Microsoft Corporation, Redmond, WA, USA) and Statistical Package for the Social Sciences (SPSS Inc., Chicago, IL, USA). A p-value smaller than 0.05 was considered significant.

3 Results

3.1 Patient characteristics

The patients (20 male, one female) were admitted for pneumonia (n = 9), line-related sepsis (n = 1), heat stroke (n = 1), peritonitis (n = 1), post-cardiac arrest (n = 2), infective endocarditis (n = 1), liver abscess (n = 2), severe gastroenteritis (n = 1), *Streptococcus bovis* bacteremia (n = 1), severe soft tissue infection (n = 1), and pancreatitis (n = 1). The average age, Acute Physiology and Chronic Health Evaluation (APACHE) II score, and abdominal wall thickness (AWTh) of the studied patients were 55.9 ± 14.0 years, 22.8 ± 9.5, and 24.6 ± 13.1 mm, respectively. Three other patients were not included in the study as they did not show any respiratory-induced IAP variation (possible wrong IAP measurement via the bladder). This could be due to any pathologies affecting the bladder compliance, and subsequently, IAP readings through the bladder.

3.2 Pearson's correlation analysis

Twenty-one different operators performed the IAP_{US2} measurements. The Pearson's correlation results between IBP, IAP_{US1}, and IAP_{US2} are presented in Fig. 2. The highest correlation was observed between IBP and IAP_{US1} with a correlation coefficient of 0.91 (R2 = 0.83) and *p*-value of 0.001. A slightly smaller correlation was also observed between IBP and the IAP_{US2} (R = 0.90, R2 = 0.81 *p*-value = 0.001).

3.3 Concordance and intra-class correlation (ICC) analysis

The concordance correlation coefficient, which presents the robustness of the IAP_{US} to track changes in the IBP, is shown in Fig. 3. A concordance correlation coefficient of 88% was observed between IAP_{US} and IBP after taking the exclusion area into account. The intra-class correlation analysis between IBP and IAP_{US} resulted in an ICC of 92.7% for the single measures, respectively (see online resource 3).

3.4 Bland and Altman's analysis

Lastly, the Bland and Altman's results are presented in Fig. 4; Table 1. This was done to have a more robust interpretation of the interchangeability of the two different measurement methods. Based on the Bland and Altman's analysis between the results from the experienced and inexperienced operators (see online resource 4), the upper and lower limits of agreement were 1.44 and − 0.99 mmHg, respectively.

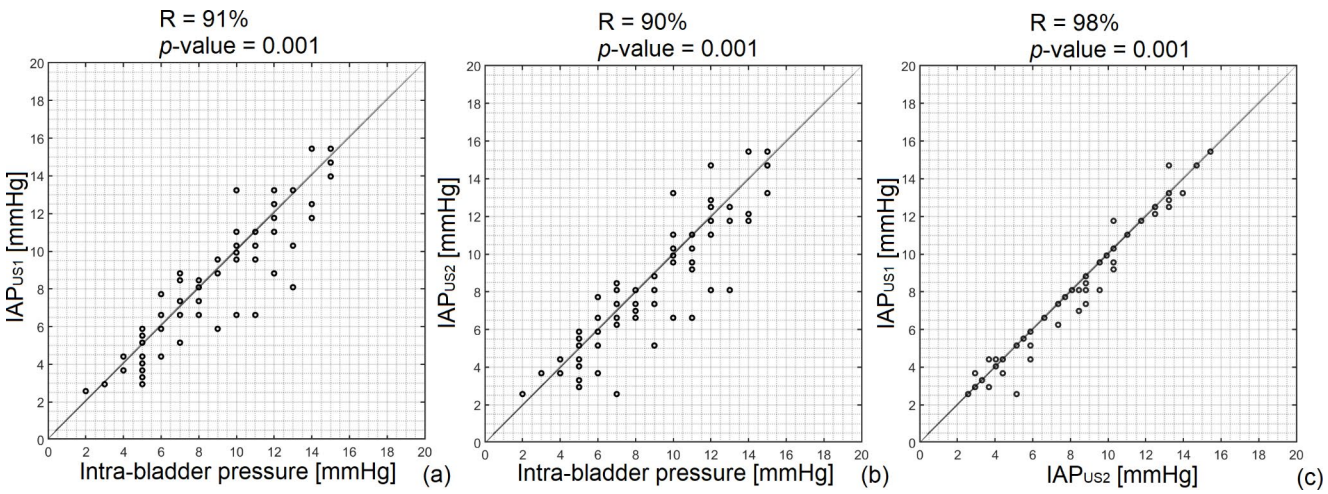

Fig. 2 Pearson's correlation and regression results showing the correlation coefficient in addition to *p*-value for each set of paired data. **(a)** Correlation results between IAP_{US1} and IBP. **(b)** Correlation results between IAP_{US2} and IBP. **(c)** Correlation results between IAP_{US1} and IAP_{US2}.

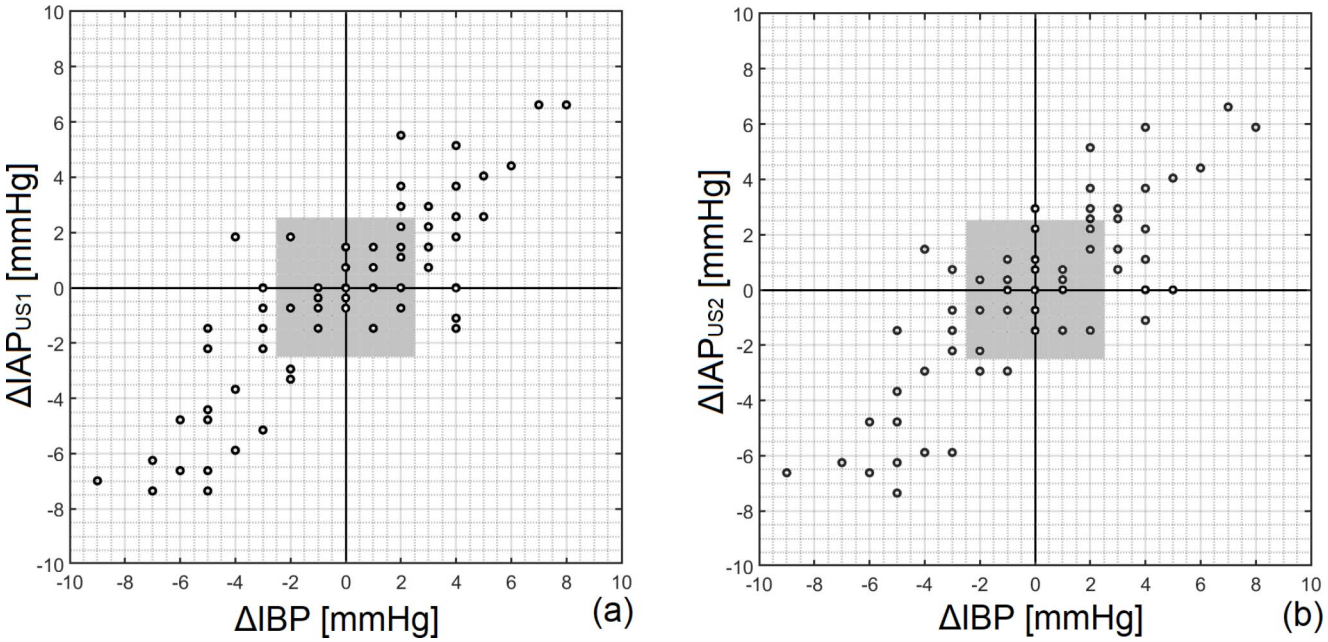

Fig. 3 Concordance plot between IAP_{US} and IBP to evaluate the ability of IAP_{US} to track the dynamic changes in IBP. A concordance correlation coefficient of 0.88 shows the robustness of the IAP_{US} in tracking the IBP fluctuations

4 Discussion

4.1 Summary

The gold standard for measuring IAP is the IBP method. However, this method is not always technically possible or feasible. The measurements vary with priming volumes and cannot be performed in the presence of bladder trauma or a neurogenic bladder. Of note, we had to exclude three patients with intra-bladder pressure-time readings that did not show any respiratory variation due to pathologies affecting bladder compliance. These cases illustrate the practical difficulties with IBP measurements in cases of anatomical problems in the vicinity of the bladder.

Direct IAP measurement is possible via the use of a percutaneous catheter [9] and pressure transducer, a balloon-tipped catheter [20] or a piezoelectric resistive membrane, but these methods are clinically cumbersome and carry infection risks [21]. Previously studied indirect methods, such as using abdominal perimeter change [22], do not correlate well with the IBP method. An abdominal wall tension measuring device looks promising, but it has only been validated in a post-mortem group [23]. Using electromagnetic waves for IAP measurement have shown promising results, however, these methods are not yet available [13, 14]. Therefore, a reliable, non-invasive alternative for measuring IAP is required [24].

In this study, we introduced and validated a novel ultrasonographic evaluation of the abdominal wall to estimate the IAP. Based on these results, IAP measurement by ultrasonography in combination with external pressure showed a significant correlation with IBP measurement. The obtained Pearson's correlation coefficients for the experienced (IAP_{US1}) and inexperienced (IAP_{US2}) operators were 0.91 and 0.90, respectively ($p = 0.001$ for both). Comparing the correlation coefficients of IAP_{US1} and IAP_{US2}, we observed an excellent agreement between the results obtained by an experienced operator and other non-experienced medical staff ($R = 0.98$, $p = 0.001$), which underlines the broad application of its use. Concordance analysis was done to evaluate the robustness of the IAP_{US} in tracking the pressure evolution and change over time. Although the concordance correlation coefficient of 88% is not excellent, it shows the ability of the IAP_{US} to keep track of the pressure changes within the abdominal compartment. To have an understanding about the reliability of the measurements, the ICC of the recorded data was assessed. The single measures ICC was 92.7%, which represents high reliability and reproducibility of the recorded data.

According to the research recommendations of the Abdominal Compartment Society, a novel measurement technique is potentially acceptable only if at least 20 relevant patients have been evaluated, and the obtained bias, precision, coefficient of variation, and percentage error are smaller than 1 mmHg, 2 mmHg, 20%, and 25%, respectively [3]. Considering the Bland and Altman's results comparing IAP_{US} with IBP, the bias, precision, and coefficient of variations were within the required quality limits for the novel US technique. However, the percentage error of the US method was 34.1% and 38.4% for the IAP_{US1} and

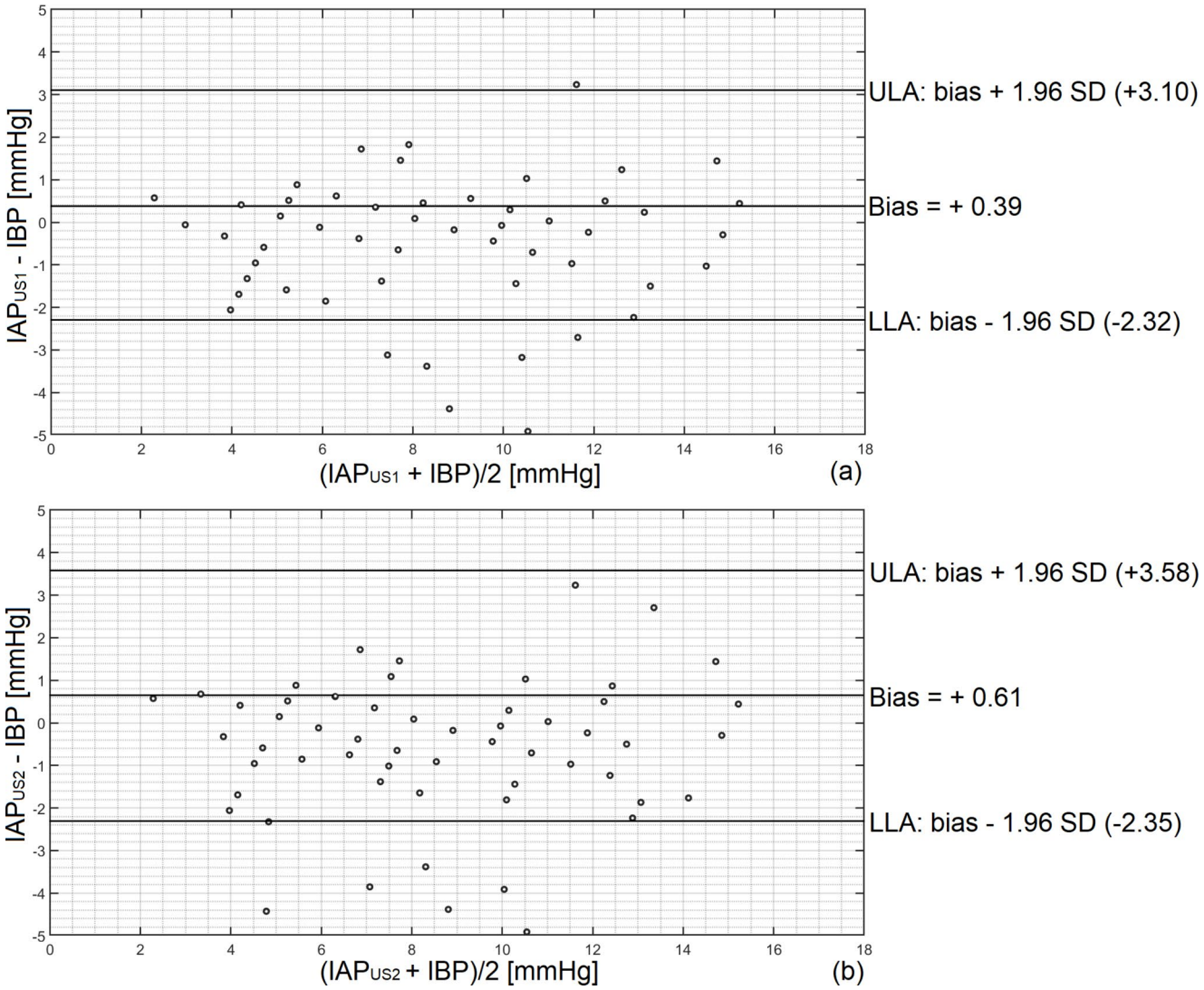
ULA: bias + 1.96 SD (+3.10)
Bias = + 0.39
LLA: bias - 1.96 SD (-2.32)
IAPUS1 - IBP [mmHg]
(IAPUS1 + IBP)/2 [mmHg]
(a)
ULA: bias + 1.96 SD (+3.58)
Bias = + 0.61
LLA: bias - 1.96 SD (-2.35)
IAPUS2 - IBP [mmHg]
(IAPUS2 + IBP)/2 [mmHg]
(b)

Fig. 4 Bland and Altman's plot for **(a)** the first (IAP_{US1}) and **(b)** the second (IAP_{US2}) set of IAP_{US} measurements. Bias, upper, and lower limits of agreement are defined as the mean difference between IBP and IAP_{US} and bias ± 1.96 precision (SD), respectively. The relatively small values of bias, precision, and limits of agreement reveal confirms the interchangeability of this ultrasound-based method with the gold standard IBP.

Table 1 Numerical results of the Bland and Altman's analysis between IBP and IAPUS.

Study method	Mean [mmHg]	Bias [mmHg]	Precision [mmHg]	LLA [mmHg]	ULA [mmHg]	PE [%]	CV [%]
IAP_{US1} vs. IBP	8.09	0.39	1.38	− 2.32	3.10	34.12	17.10
IAP_{US2} vs. IBP	7.87	0.61	1.51	− 2.35	3.58	38.37	19.20
IAP_{US1} vs. IAP_{US2}	8.09	0.22	0.62	-0.99	1.44	15.33	7.70

LLA: lower limit of agreement, ULA: upper limit of agreement, PE: percentage error, CV: coefficient of variation

IAP_{US2} results, respectively, which are slightly higher than the defined standards. However, this slightly higher percentage error could be due to wrong external pressure measurement via the water column height. In fact, this feasibility analysis was done to show this novel concept of non-invasive IAP measurement with ultrasonography, and further improvements and validations should be done before using this technique widely.

4.2 Strengths and advantages of ultrasonographic IAP assessment

The US method we describe has strengths and advantages. First, it allows direct observation of the magnitude of IAP via assessment of the depression of peritoneal lining regardless of bladder compliance. Second, this method can be repeated as often as necessary at the bedside and does not require any zeroing or reference transducer positioning, disposable equipment, and instillation of fluids into the bladder, thus avoiding the risk of infection. Third, nursing time can be saved as this technique does not require a transducer set up. Fourth, the procedure can be done rapidly within minutes although our protocol did not include timing or its duration. Fifth, ultrasonographic IAP estimation can be done swiftly if the goal is only to know if the IAP exceeds a certain critical value (e.g., > 12 mmHg, which defines screening for IAH). Finally, this technique is possible in patients who are anuric, in those who do not require a urinary catheter, or in patients who are ambulatory (e.g., pre-operative patients).

4.3 Limitations

There are still several aspects of this validation study that should be improved in future studies. First, the sample size of this study was small and did not include patients with IAP higher than 15 mmHg or patients with abdominal compartment syndrome. Therefore, the technique described is valid for the grade I IAH (IAP between 12 and 15 mmHg). The performance of this methodology for patients with higher IAH grades should be investigated further. Second, this method needs training, but as shown in the group of second operators, the method can be quickly learnt and practiced by healthcare staff with little prior ultrasonography experience. Third, as already discussed, there is not a simple standardized system to apply external pressure to the abdominal wall as one needs a tall, flat-based cylindrical bottle. However, any reasonably sized cylindrical bottle with a measurable base diameter can be used in conjunction with the principles outlined in our methodology. Fourth, it is extremely important to ensure minimal muscle tone when performing both non-invasive (IAP_{US}) and IBP measurements accurately. Nonetheless, this was not a problem in the patients under study and may be less of an issue in critically ill patients that are adequately sedated and mechanically ventilated. Fifth, we acknowledge that excessively poor abdominal wall compliance resulting from fluid accumulation and tissue edema may confound non-invasive measurements. On the same note, this technique cannot be used for patients who have any pathology of the abdominal wall as the external pressure could not be applied to them.

5 Conclusions

IAP measurement by ultrasonographic evaluation in combination with external pressure is a practical, non-invasive alternative to the IBP method and can be used in patients who suffer from intra-pelvic masses or bladder pathologies. It is a practical non-invasive alternative in patients without a urinary catheter and abnormal bladder compliance. It is a simple and straightforward technique even in the hands of inexperienced ultrasonography operators. Although there are limitations, we believe that it could potentially serve as a screening tool for IAH, complementing but not replacing the IBP method.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10877-023-01024-2.

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Authors' contributions All authors contributed to the study conception and design. The first draft of the manuscript was written by Kay Choong See and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data Availability Derived data supporting the findings of this study in addition to the processing algorithms are available from the corresponding author on request.

Declarations

Ethics Approval The study protocol was approved by the institutional review board of the local ethics committee (study number B/09/032).

Consent to participate Written informed consent was obtained from all subjects involved in the study.

Competing interests M.L.N.G.M. is Professor of Critical Care Research at the 1st Department of Anaesthesiology and Intensive Thera-

py, Medical University of Lublin, Poland. He is co-founder, past-President, and current Treasurer of WSACS (The Abdominal Compartment Society, http://www.wsacs.org). He is member of the medical advisory Board of Pulsion Medical Systems (part of Getinge group), Serenno Medical, Potrero Medical, and Baxter, and consults for BBraun, Becton Dickinson, ConvaTec, Spiegelberg, and Holtech Medical. He received speaker's fees from PeerVoice. He is co-founder and President of the International Fluid Academy (IFA). The IFA (http://www.fluidacademy.org) is integrated within the not-for-profit charitable organization iMERiT, the International Medical Education and Research Initiative, under Belgian law. The other authors have no potential conflicts of interest in relation to the contents of this paper.

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